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Ph.D. in Architecture and senior researcher at Politecnico di Milano, specialising in Virtual Heritage, BIM, XR, Digital Twin, and extended reality since 2013. He contributed to projects such as the Parliament Building of Canada, Basilica di Collemaggio, Villa dei Quintili, Appian Way, Mausoleo di Cecilia Metella, and the Church and Castle of Arquata del Tronto. With nearly 100 scientific publications, he co-directs the Gicarus ABClab and teaches at Politecnico di Milano, RLICC of KU Leuven, AUIC School, SBAPP, ABC Ph.D. School, and in 2nd-level BIM Master programs.

Elena Dellù
Archaeoanthropologist, graduated, specialised and doctorated at the Catholic University of Milan, as well as perfected in anthropology and paleopathology at the State University of Milan (LABANOF). She has about 100 contributions to national and international publications. For about 17 years she has directed archaeoanthropological excavations and research in Italy (Lombardy, Liguria, Apulia, Lazio). Since 2018 she has been an anthropologist officer of the Italian Ministry of Culture, she directs the anthropology laboratories of the Superintendency of Archaeology, fine arts and landscape for the metropolitan city of Bari (Apulia) and of the Villa Adriana and Villa d'Este institute (Lazio).

Fabio Roncoroni
Graduated in Construction Engineering from Politecnico di Milano in 2001 and earned a PhD in Geodesy and Geomatics in 2007. Currently serves as a technical manager at the General Technical Services Unit of Politecnico di Milano, Lecco Campus. Experience includes static monitoring of historic buildings, archaeological sites, and major infrastructures such as bridges and stadiums. Since 2010, responsible for monitoring landmarks like Milan Cathedral and G. Meazza Stadium, contributing to approximately 60 scientific publications.

Beyond digitisation and high-res 3D modelling of complex archaeological sites: shaping virtual heritage, XR engagement and preservation of Neanderthal Man's remains and Lamalunga cave

In recent years, the field of reality-based 3D model generation has undergone a profound transformation, impacting disciplines such as preservation, archaeology, anthropology, and virtual museums by introducing concepts like virtual heritage and extended reality (XR). The integration of digital models and 3D survey data has become pivotal, enabling immersive experiences and providing unprecedented access to previously inaccessible archaeological sites.
In 2022, the Soprintendenza Archeologia, Belle Arti e Paesaggio - Città Metropolitana di Bari embarked on a groundbreaking project to explore Lamalunga cave. This cave, housing a 172,000-130,000-year-old Neanderthal skeleton and 500 faunal remnants, became the focus of an interdisciplinary effort aimed at comprehensively documenting its morphological and typological details alongside the Neanderthal remains. Over a meticulous two-year period, the project meticulously recorded 28 previously undiscovered faunal remains using precise scanning, topographic surveying, and close-range photogrammetry. Central to this endeavor is the Science of Representation, employing advanced 3D modelling techniques such as NURBS algorithms and mesh retopology. These methods facilitated the creation of highly detailed and accurate digital replicas, capturing not only the cave's intricate physical features but also preserving the contextual integrity necessary for detailed analysis and interpretation of the archaeological findings. This study provides an overview of the digitisation process, examining both the capabilities and limitations of digital models for XR applications. By leveraging cutting-edge technology, this approach enhances preservation, accessibility, inclusivity, and global engagement with one of the world's most significant Neanderthal sites.

Giovanna Cacudi
Architect, specializing in restoring monuments at the University of Studies "La Sapienza" in Rome, was mainly concerned with protecting the architectural heritage and landscape. She has designed and directed numerous construction sites, including in Lecce the restoration of Castello Carlo V (2010-2016), the restoration of the Basilica of S. Croce (2011-2019), the restoration of the former complex of the Hospital of the Holy Spirit (2009-2019) and the restoration of the church of St. John the Evangelist (2018-2021).

Keywords:
Neanderthal Man, Lamalunga Cave, 3D Modelling, Retopology, Virtual Heritage, extended reality

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CHARTING NEW DIGITAL FRONTIERS: XR'S IMPACT ON CULTURAL HERITAGE PRESERVATION

Amidst the digital revolution, a profound opportunity arises to rejuvenate cultural heritage sites through state-of-the-art XR environments. This monumental shift is fuelled by the integration of cutting-edge technologies like 3D surveying, digital modelling, and virtual and augmented reality (VR-AR), pivotal in preserving and disseminating cultural values, tangible and intangible alike. Through these mediums, audiences embark on immersive journeys across historical epochs, accessing artefacts in their original contexts and exploring previously inaccessible locations. This democratisation of cultural wealth transcends professional and socio-cultural barriers, heralding a new era of inclusivity.
At the forefront, the European Commission's Directorate General for Communications Networks, Content & Technology champions policy coordination and funding initiatives, complementing Member States' cultural policies. Embracing digitisation, online accessibility, and digital preservation, these efforts cultivate a vibrant digital ecosystem dedicated to safeguarding Europe's rich cultural heritage (European Commission, 2021a). Central to this endeavour is the advocacy for a common European data space for cultural heritage, fostering a shared cultural identity (European Commission, 2021b).
On the national stage, Italy's Ministry of Culture leads a comprehensive digitisation initiative within the National Recovery and Resilience Plan. Integrating digitisation, innovation, competitiveness, culture, and tourism, this initiative revitalises Italy's cultural sector in line with global frameworks like the Faro Convention (Ministero della Cultura – PNRR Cultura, 2022).
In the realm of cultural preservation, collaborative endeavours among museums, archaeological sites, and cultural institutions propel the digitisation of artefacts, monuments, and historical complexes, fostering immersive experiences known as "Virtual heritage" (Champion, 2021; Huggett, 2020; García-Bustos et al., 2023). This transition towards virtual realms merges 3D modelling and simulation techniques with evolving user interactivity, thereby facilitating knowledge processes.Virtual tools offer varied pathways for accessing and analysing data within spatially immersive domains (Rodriguez-Garcia et al.,2024). However, while virtual heritage reconstructions hold promise as innovative information systems, they often serve primarily as alternative modes of archaeological illustration and presentation, rather than driving archaeological inquiry forward.
Of critical importance is 'how' these digital worlds are created, as this aspect can significantly influence subsequent experiences, digital proxemics and interactions within virtual environments. In these environments, user engagement is pivotal, as decisions made can wield significant influence over outcomes, thereby resulting in diverse user experiences. In the domain of scientific inquiry, the Altamura cave emerges as an invaluable natural laboratory teeming with potential (Fig.1). Its unique amalgamation of typological and morphological complexity positions it as a focal point for both archaeological and anthropological investigations, providing a rich canvas for the digital representation and communication of values within intricate landscapes. However, the delicate fragility of the cave necessitates a meticulous equilibrium between preservation efforts and the precise documentation and representation of its contents. Despite previous expeditions predominantly focusing on paleoanthropological inquiries, the cave's broader archaeological context and karst formations have often been relegated to the periphery of exploration. To truly grasp the cave's significance, comprehensive investigations spanning disciplines such as representation, archaeology, geology, and environmental science are imperative.

Fig. 1 - The entrance to the Altamura cave presents itself as an impressive tunnel descending about 10 meters into the depths of the earth and limestone rock, framed by a picturesque backdrop of Mediterranean vegetation.

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As archaeologists navigate the multifaceted terrain of modelling complex scenarios, they are confronted with the formidable challenge of mastering cutting-edge software. These tools serve as the conduit for transforming raw data derived from laser scanning and digital photogrammetry into immersive digital models, effectively breathing life into ancient artefacts. Yet, within this digital labyrinth, lies a crucial component that cannot be overstated: implementing proper 3D modelling techniques grounded in the interpretation of sources. The latter serves as the cornerstone of reliability in model creation. It involves decoding digital outputs, extracting essential information, and translating it into a comprehensive and scientific representation of surveyed artefacts. One might envision this process akin to unravelling a cryptic message, where each pixel and polygon holds a pivotal piece of the puzzle. This meticulous endeavour involves transitioning from intricate polygon meshes and textures to sleek 2D/3D geometric entities that vividly depict the objects of interest. Advanced laser scanning, photogrammetry, and digital modelling methodologies have been harnessed to surmount these obstacles. These techniques meticulously survey and digitally reconstruct the intricate karst complex (Fig. 2), striving to establish a scan-to-BIM-to-Extended Reality (XR) process. This holistic approach yields datasets that illuminate both karstological and paleoanthropological facets, catalysing the development of new preservation strategies and enriching scholarly discourse within the XR domain.

PRESERVING HERITAGE: THE IMPACT OF DIGITAL AND 3D TECHNIQUES ON ARCHAEOLOGICAL STUDIES

The fusion of digitisation with advanced 3D surveying techniques and 3D modelling has become indispensable for the meticulous documentation and analysis of prehistoric sites and archaeological artefacts.

In recent years, a surge of scholarly endeavours has embraced this cutting-edge methodology, resulting in intricate and precise digital representations that revolutionise site acquisition and enhance reflexivity in archaeological excavation practices. This convergence represents a significant intersection of archaeology with advancements in computer science, reshaping how archaeological data is captured and interpreted. The advent of digital technology has unlocked heuristic potential in archaeology, particularly in spatial data analysis, offering promising avenues for understanding complex archaeological landscapes. The comprehensive overview by Mohammed Oludare Idrees and Biswajeet Pradhan (Idrees & Pradhan, 2016) offers insights into modern cave surveying with terrestrial laser scanning, establishing a universal standard method adaptable to different cave geometries.

Recent advancements in cave digitisation have facilitated the analysis of archaeological data, enabling the synthesis of spatial analysis tools and complex 3D boundary models across various studies (De Waele et al., 2018; Bayarri et al., 2023; Pan et al., 2023; Pfeiffer et al., 2023; Wisher et al., 2023; Cardia et al., 2024; Ka□uk et al., 2024; Kartini et al., 2024; Oliinyk et al., 2024; Pereira et al., 2024). However, challenges persist in integrating digital technologies into archaeological research, particularly in addressing the complexities of digital models. Techniques like retopology and mesh simplification have emerged as crucial elements in optimising the representation of caves and archaeological sites, ensuring geometric reliability across various scales of analysis (Cignoni et al., 2008; Franc, 2002; Guidi & Angheleddu, 2016; Bahirat et al., 2018; Gonizzi Barsanti et al., 2023). By adjusting the polygonal mesh size associated with each 3D model, the

Fig. 2 - The northern branch characterised by the Altamura Limestone Formation.

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Fig. 3 - Some of the faunal remains digitised during the initialsurvey campaign of 2022.

Fig. 4 - The "Apse of Man" and the remains of the Neanderthal man immersed in limestone concretions.

representation could be optimised across various scales of analysis. Nevertheless, persistent challenges arise, particularly in the management and monitoring of complex scenarios over time, where understanding the physical, formal, and spatial relationships among excavated objects and their changes is crucial.
In this context, the emergence of Virtual Heritage marks a transformative era for cultural preservation and dissemination, offering immersive experiences and expanding knowledge access through digital platforms (Banfi, 2023).
Despite this, leveraging digital resources for heritage promotion faces hurdles, as their full potential remains untapped. Integrating 3D modelling with XR-based tools promises unprecedented interactivity, fostering virtual heritage experiences conducive to acquiring fresh insights and enriching the collective understanding of our cultural heritage.The integration of digital technologies presents a compelling avenue for advancing the exploration of prehistoric caves and archaeological remnants, safeguarding them for future generations, and fostering broader access to insights within and beyond the academic community. This process underscores the importance of critical re-elaboration of sources and collected data, guiding the selection and use of state-of-the-art 3D modelling tools to manage complex scenarios effectively.

FROM KARST FORMATIONS TO HUMAN HERITAGE: THE WONDERS OF LAMALUNGA CAVE

The Altamura cave, nestled in the picturesque Apulia region of Italy, has earned international acclaim for harbouring the remains of the "Altamura Man", a Neanderthal believed to have roamed the Earth some 150,000 years ago. In 1993, a group of Apulian speleologists stumbled upon an undiscovered cave while exploring karstic formations in Altamura. Inside, they unearthed a paleo surface adorned with faunal relics dating back around 40,000 years (Fig. 3). Additionally, within a small natural recess, they discovered

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remarkably well-preserved remains of a Homo neanderthalensis, estimated to be between 172±15 and 130.1±1.9 thousand years old. (Fig. 4). This discovery is considered the most ancient and well-preserved Neanderthal specimen known to date. Promptly recognising its cultural significance, the Ministry of Cultural designated the cave and its artefacts as of paramount importance (Pesce Delfino & Vacca 1993a; Pesce Delfino & Vacca 1993b; Pesce Delfino & Vacca 1994; Pesce Delfino 1995; Micheli et al. 1996; Caramelli et al. 2010; Manzi et al. 2010; Lati et al., 2015; Di Vincenzo et al. 2019; Riga et. al. 2020) and more than 500 faunal remains deposited between 45-30 ka (Giacobini et al, 2010; Fiore et al, 2018).
Known as the "Lamalunga Cave", it lies near the bustling city of Altamura, attracting extensive scientific study aimed at enhancing our understanding of human evolution. The exceptional preservation of the human specimen within the cave has provided researchers with a unique opportunity to explore Neanderthal morphology, behaviour, and lifestyle. The integrity of the Altamura Man has allowed exhaustive analysis of its skeletal remains, yielding valuable insights into its evolutionary path and genetic connections with modern humans. These studies have shed light on dietary practices, health, and socio-cultural aspects of this ancient human population. Archaeologically, the cave of Altamura is a treasure chest, which until now has revealed the presence of faunal and anthropological remains (but for which the possibility of identifying archaeological finds is not excluded), offering glimpses of millennia of human attendance. Beyond its scientific importance, the cave holds cultural significance for the local community and Italy as a whole. Through exhibitions, events, and educational programs, the cave and its inhabitants have become symbols of human heritage and scientific inquiry, inspiring efforts to preserve our shared archaeological and natural heritage. From a geological perspective, the cave's bifurcated morphology imparts it with distinct characteristics. The northern branch extends over an impressive 1050 cubic meters, boasting a myriad of intricate karst formations. Conversely, the southern branch, covering approximately 800 cubic meters thus far, offers a distinct contrast in its geological features. The geological stratum underlying the Altamura cave, identified as the "Altamura Limestone Formation" within the Senonian Series, is emblematic of the area's geological heritage (Agostini, 2010). Its entrance, perched at an elevation of 508 meters above sea level, marks the apex of a highly evolved epicarst system, characterised by diverse base levels.
The cave complex comprises primarily two sub-horizontal galleries, delineated by a central chamber inundated with sedimentary debris. Within this cavernous expanse, concretionary cycles of varying morphologies and mineralogies bear testimony to fluctuating microclimatic conditions, air currents, and geochemical compositions of percolating waters. Noteworthy deposits of faunal and paleoanthropological significance adorn the surface and recesses of the main gallery, juxtaposed against stalagmitic formations and globular incrustations, each revealing subtle nuances of environmental evolution and human occupation (Branca & Voltaggio, 2010).
Notably, the so-called "Apsis of Man" houses a plethora of exceptionally preserved Homo neanderthalensis remains, ensconced within elaborate 'coralloid' formations indicative of calcite deposition processes (Branca & Voltaggio, 2010; Vanghi et al, 2017). Since the discovery of its paleoanthropological and faunal wealth, the Lamalunga Cave has served as a veritable crucible of multidisciplinary inquiry, spanning three decades of concerted efforts aimed at elucidating its paleoanthropological heritage, faunal taxonomy, calcitic formations, and temporal context. Presently comprehensive conservation endeavours are underway, encompassing the multifaceted heritage of archaeological, historical, ethno-anthropological, and landscape significance. This holistic approach encompasses not only maintenance and preservation activities but also rigorous oversight of interventions, promotion of scholarly studies, cultural initiatives, and collaborative research endeavours with regional entities, universities, and cultural institutions. Against the backdrop of contemporary climatic fluctuations, novel methodologies for remote monitoring and digital preservation have emerged, underscoring a commitment to long-term stewardship and public engagement with this invaluable cultural treasure.

PROJECT OBJECTIVES: FROM DIGITISATION TO NEW FRONTIERS IN VIRTUAL HERITAGE

In 2022, under the guidance of Giovanna Cacudi, the Soprintendenza Archeologia, Belle Arti e Paesaggio - Città Metropolitana di Bari initiated a pioneering project to explore the Lamalunga cave, led by Elena Dellù, the official responsible for its preservation. Supported by regular funding from the Ministry of Culture, this initiative reinvigorated research efforts (Signorile, 2023). In this context, the GIcarus-ABCLab of the Politecnico di Milano, under the scientific supervision of Fabrizio Banfi, contributed to the surveying, documenting, and digitising of the cave.

Fig. 5 - SKY TG 24. "Archeologia virtuale, così rinasce l'uomo di Neaderthal". The digital survey operations required specific precautions to minimize the impact of the operators' presence in the Man's Apse. These measures included using masks and gloves, adhering to designated time slots to prevent oxygen depletion, and allowing only one operator at a time for work in close proximity to the Neanderthal remains. Source: Pedeferri, J. (2024) https://tg24.sky.it/tecnologia/now/2024/01/24/uomo-neanderthal-digitale-altamura-archeologia-virtuale

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The first survey campaign in 2022 marked a crucial milestone, enabling meticulous surveying, recording, digital rendering, and georeferencing of Neanderthal skeletal remains and 28 faunal remnants (Fig. 6). This comprehensive digital twin offered a non-invasive method to examine fragile specimens, mitigating the risk of damaging the cave's limestone substrate. Scholars could study the artifacts from multiple perspectives and perform precise measurements without physical contact, using high-resolution models and advanced representations. The digital twin was particularly beneficial for osteological studies, lesion and anomaly assessments, and anatomical reconstructions, aiding in the identification of unique features through comparative analysis with other fossil specimens. Additionally, it was used for outreach and educational purposes, facilitating interactive simulations, web-VR experiences, and educational materials that engage the public with the cave's prehistoric legacy (Pedeferri, 2024).

Building upon this foundation, following the second survey campaign, the study laid the groundwork for the comprehensive digitisation of the cave. After the 2022 surveying, a substantial volume of data was meticulously processed, integrating the new segment of the model corresponding to the northern branch with its southern counterpart. For the first time in the cave's history, the northern branch was documented and integrated within a digital ecosystem capable of disseminating and communicating its contents through novel virtual modalities.Rooted in scholarly expertise and leveraging advanced modelling, digital prosody, retopology, and XR development, the research aimed to enhance the virtual accessibility of the cave, surpassing previous efforts from 2022, while addressing emerging challenges in the realms of virtual heritage and the metaverse. These pathways encompass:

Data collection: it is dedicated to the meticulous surveying, analysis, and documentation of the cave's morphological and typological intricacies across varying scales. Such endeavours serve as the foundational bedrock for a comprehensive scan-to-BIM-to-XR digital restitutive process, facilitating the integration of both branches of the cave into a singular immersive environment.

Model generation: it involves the creation of digital outputs tailored to diverse analytical purposes, including the examination of major degradation pathologies within cave environments and the digitised representations of bone remains. This endeavour necessitates the evaluation and refinement of various nodal-representation techniques to ensure the creation of lifelike digital models conducive to XR environments, devoid of latency, connectivity issues, or navigational impediments. The method's reliability is elucidated through comprehensive assessments detailing its requirements, advantages, and limitations.

Information mapping: semantic enrichment of digital outputs is undertaken to facilitate archaeologists' and anthropologists' investigations into the cave's environments, as well as the study of Neanderthal Man and faunal remains.

Information sharing: this phase comprises three novel distinct lines of XR development, each tailored to cater to diverse users and devices, with the overarching goal of enhancing accessibility and inclusivity of the cave treasures. These ongoing developmental trajectories will be expounded upon within the paper, showcasing the tangible outcomes achieved within this specialised domain.

THE INITIAL 3D SURVEY CAMPAIGN (2022): THE NORTHERN BRANCH OF THE CAVE, THE NEANDERTHAL MAN, AND FAUNAL REMAINS

The exploration of Lamalunga cave, renowned for its significance in archaeological research, particularly in unveiling the path leading to the Man's Apse, was undertaken to meticulously define its geometry and construct a comprehensive digital model (Banfi et al, 2023). Beyond the cave's

Fig. 6 - Topographic and Laser scanning Surveying operations conducted in the northern branch of the cave

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confines, the survey extended to the surrounding terrain, delineating pathways, subterranean chambers, and offering a panoramic overview of the region's restricted-access zones. This meticulous endeavor began after a thorough inspection conducted in September 2022. The survey unfolded through a series of meticulously orchestrated phases. Initially, a network of reference points was established on the surface, employing advanced Global Navigation Satellite System (GNSS) instrumentation to seamlessly integrate the survey within the National Cartographic System framework. Within the cave's intricate expanse, a topographic network was meticulously erected to serve as a foundational reference for the subsequent laser scanning expedition. Checkerboard targets, strategically positioned as control points, punctuated the cave's interior, facilitating precise georeferencing. Subsequently, an exhaustive laser scanning operation was undertaken to meticulously capture the intricate morphology and features of the cave system. Concurrently, a detailed photogrammetric survey, focused on the Man's Apse and areas housing significant findings such as fauna remains, further enriched the 2022 dataset. This photogrammetric approach, aligned with the topographic network, leveraged checkerboard targets to ensure spatial congruity.

The external terrain surrounding the cave's entrance witnessed the establishment of four reference points, meticulously measured utilising GNSS instruments in static mode. These reference points, meticulously positioned using topographical nails, served as anchorage for subsequent surveying endeavours. Employing a network of permanent stations within the Apulia region, particularly the Poggiorsini station (POGG), ensured the precision and fidelity of these measurements, facilitating seamless integration with existing cartography. Within the cave's confines, a meticulously crafted topographic network, comprising strategically positioned markers affixed to the cave vault, served as a pivotal reference for subsequent georeferencing endeavors. Leveraging the Leica TPS1200 total station, measurements were conducted from a network of seven station points, meticulously structured to ensure comprehensive coverage. These measurements yielded 28 Ground Control Points (GCPs), pivotal in georeferencing the ensuing terrestrial laser scanner point cloud. A commensurate effort was undertaken to establish GCPs outside the cave, further bolstering the spatial fidelity of the dataset.The laser scanning campaign, facilitated by the FARO Focus 3D X 130 HDR, was meticulously orchestrated to ensure optimal coverage and density of captured points across the cave's interior and exterior surfaces. A total of 121 scans were meticulously executed, with particular emphasis on internal areas of significant interest, where colour scans further enriched the dataset. The critical juncture where the cave interior meets the external terrain necessitated a meticulous approach, involving separate surveys linked through scans conducted within the well's confines. Precision in georeferencing was ensured through the strategic distribution of spherical targets within the meticulous execution of scans from varying vantage points. Thirty-by-thirty-millimeter checkerboard photogrammetric targets, meticulously positioned before scan execution, served as pivotal reference points, facilitating seamless integration within the broader spatial framework. The survey culminated in the comprehensive documentation of the Man's Apse (Fig. 7) and other areas of archaeological significance, achieved through a harmonious fusion of laser scanning and photogrammetry.

This multi-sensor, multi-scale approach, emblematic of contemporary 3D surveying practices, yielded an array of graphical outputs, including colored point clouds and mesh models at varying resolutions.

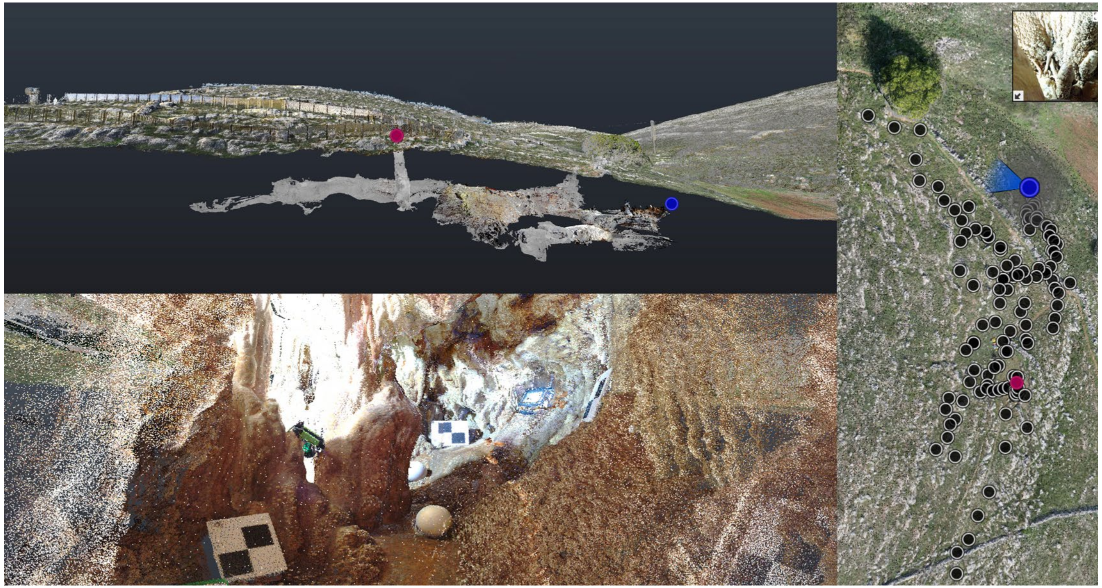

Fig. 7 - Point clouds resulting from the laser scanning surveying of the northern branch. The images illustrate the scans conducted in correlation with the data obtained from the exterior, the Neanderthal man's apse (in blue) and the entrance (in red).

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These outputs found application across diverse domains, ranging from on-screen visualization to the creation of 2D drawings and the management of 3D models through interactive 3D PDFs and immersive XR environments. The photogrammetric survey leveraged state-of-the-art equipment, including a Canon 5DSR camera with a full-frame sensor, a Canon EOS 5D Mark IV, a GoPro Hero 11, a professional endoscope Depstech DS300, and a Ricoh Theta Z14K 360° camera. Specialized lenses, including a Canon 20mm f/2.8 for cave surfaces and a Canon 35mm f/1.4 for bone remains, ensured optimal image quality and detail capture. To mitigate challenges posed by limited lighting conditions, synchronised shooting flashes were deployed, guaranteeing uniform illumination across the cave's diverse topography. This approach culminated in the generation of 3D textured models of identified cave sections, alongside 11 highly detailed models of processed bone remains encapsulated within 3D outputs and high-resolution textured mesh models. Designed for easy sharing and management, even among individuals lacking prior experience with 2D and 3D data, these documents facilitated comprehensive analysis and metric evaluation of both the cave environment and the associated bone artifacts (Figg. 8-9).

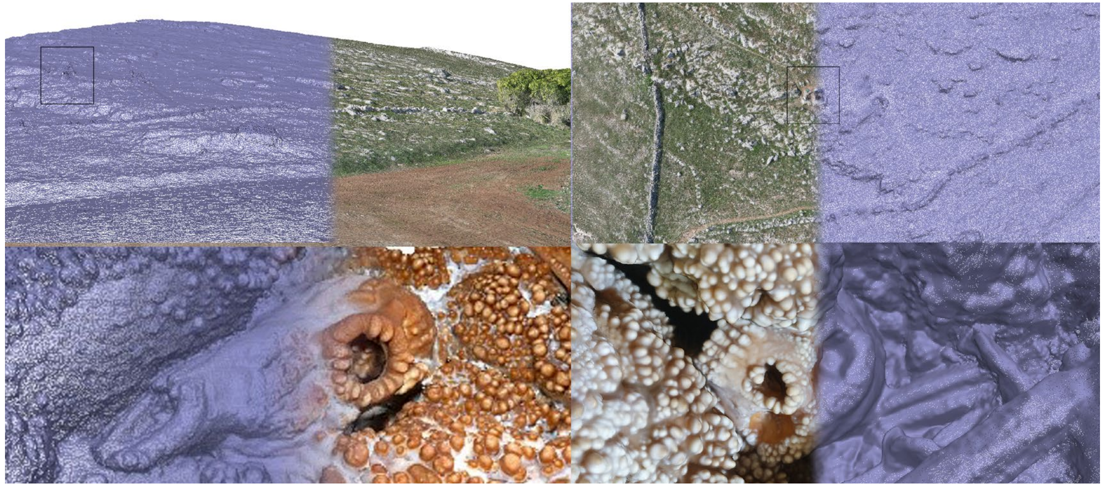

Fig. 8 - High-res digital photogrammetry outputs: from dense point cloud to the textured mesh models of the exterior of the cave with the identification of the entrance, remains of fauna, and the Neanderthal Man

RESEARCH PROGRESS: THE SECOND 3D SURVEY CAMPAIGN (2023) OF THE SOUTHERN BRANCH OF THE CAVE

The 3D surveying conducted on the southern branch of the Lamalunga cave constitutes a pivotal undertaking intricately interwoven with prior scholarly endeavours, particularly those undertaken during the autumn of 2022. This phase of meticulous investigation represents the culmination of exhaustive data acquisition

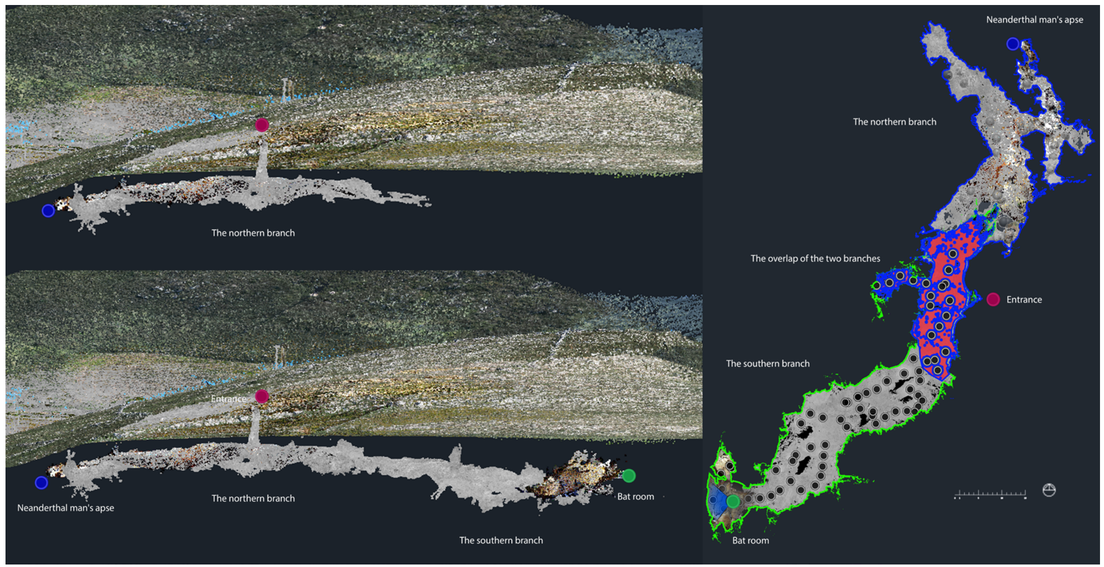

Fig. 9 - Overview of the laser scanning surveying of the Altamura cave: the point clouds corresponding to the northern branch (in blue) and the southern branch (in green) include an overlapping area (in red) to enable the topographic georeferencing of the two campaigns (2022 and 2023).

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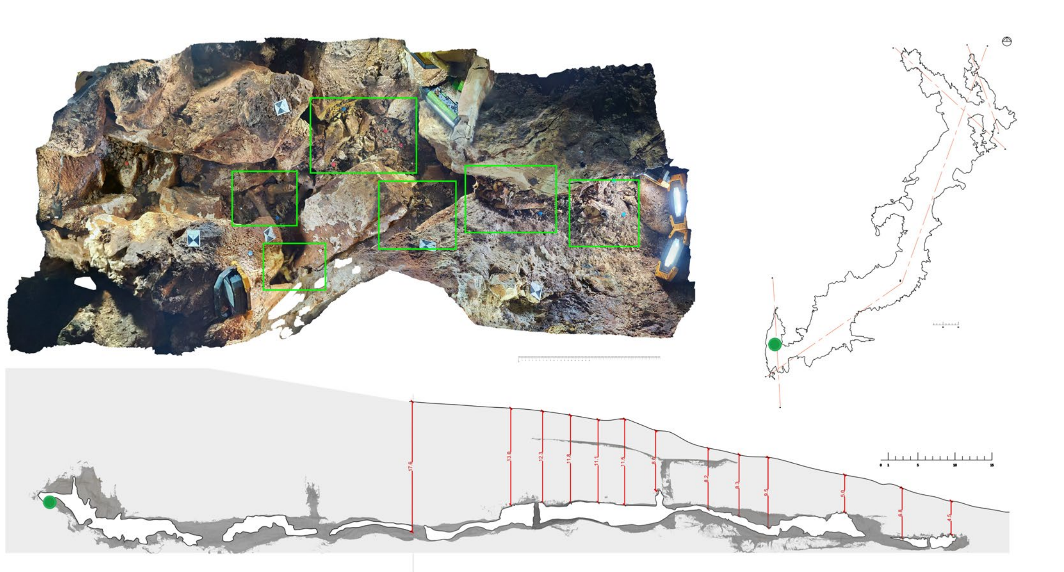

Fig. 10 - Digital outputs generated from the southern branch of the cave in 2023, encompassing the comprehensive layout and cross-sections of Lamalunga Cave, comprising both its northern and southern branches, along with an orthophoto capturing newly discovered faunal remains in the bat room.

endeavours essential for the construction of a comprehensive virtual model of the cave system. This subsequent phase seamlessly integrates with its antecedent counterpart, leveraging identical instrumentation and data processing methodologies. The survey unfolds through a bifurcated approach, comprising a foundational support topographic surveying alongside a concurrent laser scanning expedition, each meticulously executed within the confines of the cave's labyrinthine passages (Fig. 9). The primary objective of supporting topographic surveying lies in the establishment of a robust network of reference points, thereby delineating a localised spatial framework conducive to the precise georeferencing of acquired scans.
Utilising cutting-edge instrumentation, exemplified by the Leica TPS 1203 total station, this phase orchestrated the measurement of 41 Ground Control Points (GCPs), strategically positioned across a network of 10 measurement stations. To mitigate potential measurement inaccuracies, a strategy of redundantly measuring select targets from multiple vantage points was employed, ensuring a high degree of fidelity.
Conversely, the laser scanning campaign, conducted utilising the Faro Focus 3D HDR 130 apparatus, extended its purview to encompass all accessible regions within the southern cavity of the cave. Comprising a total of 73 scans, each comprising an impressive 44 million data points of exceptional quality (designated as 3X), this endeavour aimed to capture the intricate topographical nuances of the cave's rocky interiors with unparalleled precision. Notably, scans executed along the approach trajectory leading to the "bat room" (Figg. 10-11) were conducted in monochromatic mode, while those within the confines of this chamber were augmented with colour data, facilitating a more nuanced

Fig 11. - Analysis and documentation of newly discovered faunal remains in the bat room (above).

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Below: 3D outputs of the newly discovered faunal remains in the bat room: from point cloud and mesh model to elevation model and measurable, remotely analyzable textured mesh model.

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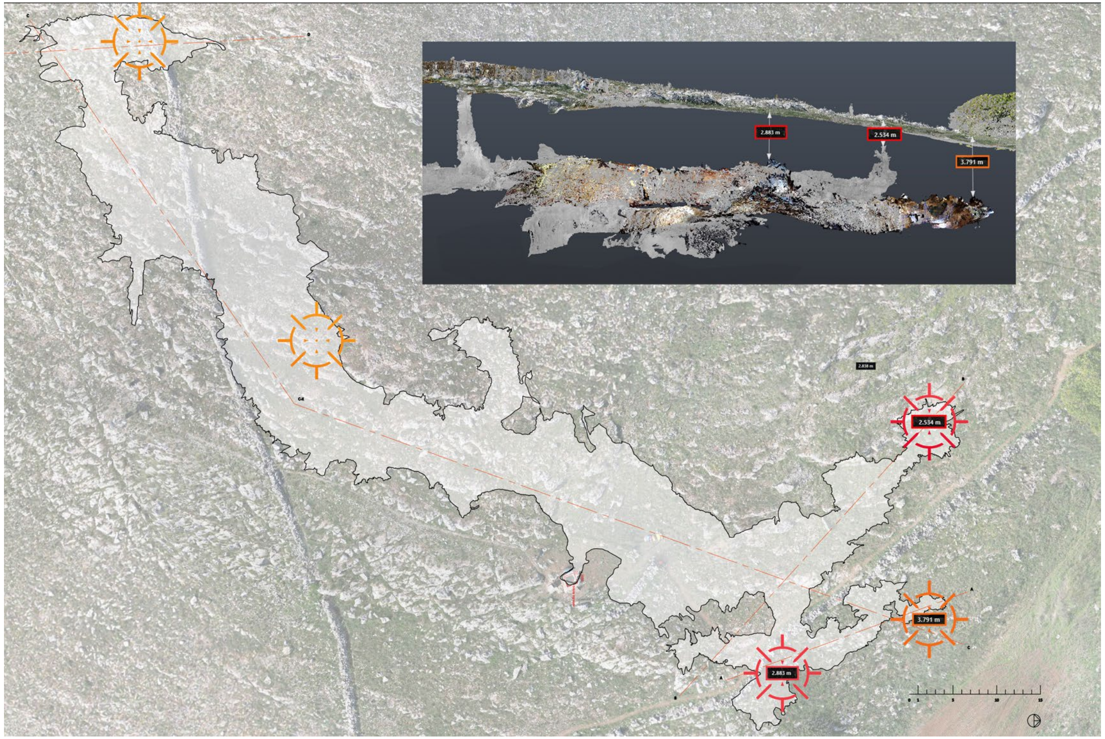

Fig. 12 - The overall plan of Lamlaunga Cave with the identification of potential critical areas near the surface.

portrayal of spatial characteristics. Critical to subsequent georeferencing endeavours, a constellation of GCPs, including spherical targets and checkerboard flat targets, were strategically dispersed throughout the scene. Of particular note, 41 of these targets were subjected to measurement via the total station, ensuring cross-validation of spatial coordinates. Leveraging state-of-the-art Faro SCENE software, the georeferencing process yielded a marginal uncertainty averaging ± 4mm, underscoring the precision of the undertaken efforts. Upon the acquisition of a comprehensive point cloud dataset representing the southern branch, efforted transition to the alignment of this dataset with its northern counterpart and photogrammetric ouputs such as the newly discoverd faunal remains (Fig. 11). Facilitated by the Iterative Closest Point (ICP) algorithm, this alignment operation harmonised scans common to both surveys, notably those encapsulating the environs proximate to the cave's entrance tunnel. Noteworthy was the meticulous nature of this alignment process, culminating in an average uncertainty of ± 3mm, affirming the fidelity of the resultant spatial representation. Georeferencing internal data with external data has pinpointed 5 potential critical zones near the surface (Fig. 12). Specifically, two were located in the southern branch, spaced 5 to 7 meters apart, while in the northern branch, three zones were identified: two at distances of 2.5 meters and 2.8 meters from the surface respectively, and a third at 3.7 meters, coinciding with the Neanderthal remains This will support ground-penetrating radar (GPR) or georadar investigation operations, enabling detailed exploration of terrain and materials through the propagation and reflection of electromagnetic waves produced by the system itself. By transmitting electromagnetic waves into the ground and analysing the reflected signals, GPR can detect and map buried artifacts, changes in material properties, voids, and other subsurface features with precision.

THE 3D MODELLING PROCESS OF THE LAMALUNGA CAVE, THE NEANDERTHAL MAN, AND THE FAUNAL REMAINS

The 3D modelling project embarked on dual objectives: crafting precise digital representations for diverse XR prototypes to enable remote analysis of bone surfaces and calcitic concretions within their contextual landscapes, and developing immersive virtual experiences where user interaction with the models took center stage. The overarching ambition was to meticulously map attributes such as distribution, consistency, calcite detachments, organic material degradation, and anthropometric measurements. Simultaneously, these models were envisioned as central figures in a range of XR experiences tailored for interaction across various devices, from tablets and smartphones to cutting-edge VR headsets.Transforming point clouds into mesh models posed challenges due to the intricate nature of high-resolution meshes. A methodical approach involving identification, analysis, interpretation, and deep understanding of unique artifacts was crucial for creating accurate and semantically enriched 3D representations suitable for XR environments. While topographic surveying, laser scanning, and close-range photogrammetry yielded extensive data, it became evident that relying solely on

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automatic or semi-automatic digital tools was insufficient for comprehensive digitisation and semantic categorisation of archaeological elements. This realisation sparked a focused effort to effectively address the representation of complex elements.Consequently, the 3D modeling of cave components integrated three distinct methodologies tailored to specific requirements. The first approach involved detailed analysis, interpretation, and ultra-resolution 3D modelling of the cave's elements of interest, including:

- every Neanderthal bone within the apse context to facilitate comprehensive archaeological, anthropological, and conservation studies;
- sauna remains, laying the groundwork for unprecedented insights into the cave's history;
- stalactites and stalagmites, the captivating cone-shaped formations adorning the cave's ceiling and floor, embodying the geological wonder of subterranean landscapes.

These efforts marked a significant milestone in the documentation and exploration of the cave, offering unprecedented insights and enhancing our understanding of its rich history.The primary goal was to achieve high levels of detail (LOD) and information (LOI) in the models by decomposing them into sub-elements capable of representing semantic entities beyond the mere geometric attributes of the cave. The applied approach aimed to address the limitations of automatic digital tools, which, while facilitating the transformation of simple points in space and the generation of meshes from point clouds and mesh-to-NURBS approaches, may lack the flexibility to generate relevant sub-elements derived from the phases of analysis and interpretation of the data (Fig. 13).
Particularly noteworthy was the integration of 3D drawing and modelling techniques with NURBS algorithms, bridging a significant generative gap while ensuring autonomy in representing various elements without compromising the interpretative and digitisation phases. 3D drawing provided modellers with precise control over the LOD in the interpolated surface, facilitating a delicate balance between model complexity and the available quantity of data, thereby meeting project requirements without unnecessary computational burden. In this scientific discourse, the concept of retopology emerged as a fundamental technique addressing the topological intricacies inherent in polygonal meshes (Cignoni et al. 1998; Franc et al., 2002; Bahirat et al.,2018; Gonizzi et al., 2022).
Its primary focus lies in arranging faces to ensure their suitability for subsequent stages, notably texture mapping, which enhances visual appeal through image-based techniques. Conversely, the decimation process aims at reducing polygonal complexity without considering topological characteristics. Thanks to the use of Bsurfaces (a modelling and retopology tool - Blender addon), it was possible to combine Bezier curves to generate polygonal surfaces. They have been used to build both open and closed shapes composed of quadrilateral faces, allowing the modeller to see how it affects the resulting surfaces in real-time.
The post-processed mesh models were subsequently converted into closed NURBS and volumetric models, ensuring the ability to extract numerical information such as volumes, areas, and thicknesses of digitised elements.
This seamless continuity eradicated any visible discontinuities that might compromise the model's integrity, thereby ensuring a cohesive representation of both Neanderthal and fauna bone remains (Fig. 13). By representing complex surfaces with a specific number of control points, NURBS effectively reduced the computational load and resource consumption required for data management, optimising efficiency in the volumetric modelling process. Furthermore, the precise interpolation capabilities inherent in NURBS proved indispensable, adeptly conforming to input data, even amidst constrained sampling. This proficiency ensured the faithful rendition of the bones' intricate details, striving, when possible, to virtually disentangle bones from the calcite concretions adorning the walls of both the man's alcove and the cave.

Fig. 13 - Automatic retopology applied to the skull lacks parametric control in specific areas. The transformation from a high-resolution mesh model to a quadrilateral-based model occurs uniformly across all selected surfaces, without differentiation.

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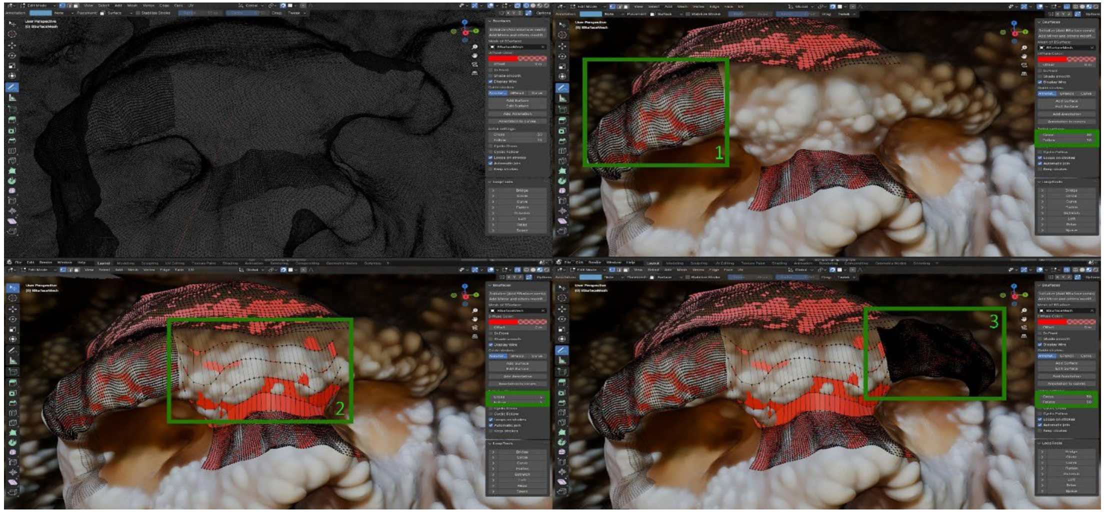

Fig. 14 - Before transforming the high-resolution mesh model (top left) into the NURBS model, several steps were implemented to reduce the number of triangular surfaces by converting them into quadrilateral faces. This process involved utilizing 3D drawing and parametric control of internal subdivisions, enabling the transition from dense meshes (1,3) to more simplified meshes (2) as required.

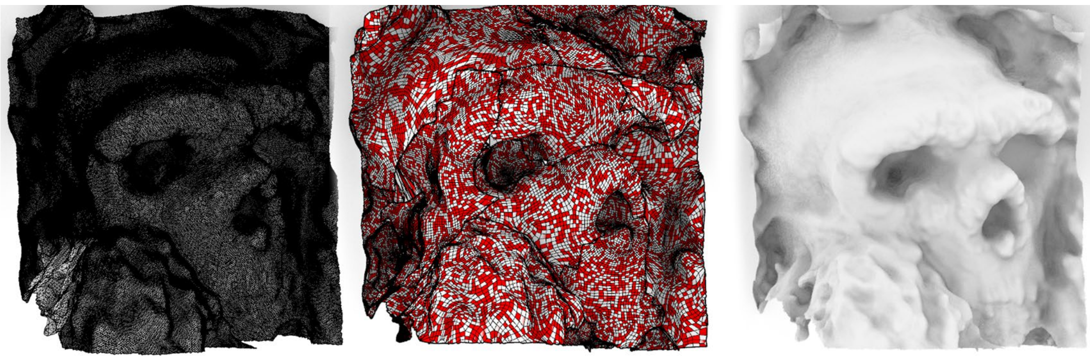

Fig. 15 - The NURBS model obtained through the proposed process—depicted as the final NURBS model on the right—is around 30 megabytes in size, a reduction of 20-fold compared to the initial photogrammetric model on the left. The transformation from triangle-based mesh to a model divided into quadrilateral faces has allowed to maintain the complexity and LOD while making the model as performant as possible for XR environments.

Such meticulous efforts not only enriched the comprehension of their morphology and composition but also contributed to a more nuanced understanding of the archaeological context.

Figures 13, 14 and 15 illustrate the process applied to the cranial remains of the Neanderthal specimen. Through a comprehensive analysis of the dataset, precise points were discerned, facilitating a focused virtual extraction procedure of the skull from the encrusted limestone, eschewing the reliance on a mesh model. With the delineation of geometric points and boundaries, data interpolation ensued, incorporating both points and external profiles, culminating in the creation of a quadrilateral face. Leveraging 3D drawing, it was possible not only to outline edges and incorporate triangular surfaces for transformation but also to adjust the LOD according to requirements, alternating between models ranging from several gigabytes to mere megabytes in size. 3D drawing was executed freehand, relying on the portions of the mesh to be improved or converted as reference. This meant that retopology wasn't dependent on an automatic triangulated mesh tool to reduce the model's weight while maintaining accuracy. Instead, it relied on a flexible and precise method of surface transformation through 3D drawing (Fig. 14).

The geometric fidelity of the resultant model underwent rigorous scrutiny via an automatic verification system (AVS) adept at calculating the standard deviation between the point cloud and the rendered model. This meticulous validation process served as the cornerstone for subsequent phases in the digitalisation endeavour, encompassing prominent artefacts such as the cranial structure, remnants of identified fauna, and key geological formations within the cave complex, including stalactites and stalagmites.

The copiousness of the acquired dataset portends versatility, wherein future exigencies may necessitate the extension of this process to encompass novel discoveries or unexplored faunal remnants, thereby enriching the repository of 3D models available for scholarly inquiry and public

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dissemination. Concurrently with the finalisation of high-res modelling for the primary cave elements, addressing the management, modelling, and subsequent transformation of initially omitted survey data required the establishment of a sophisticated yet user-friendly digital environment within XR development frameworks. The inherent discretisation of polygonal meshes, which introduced approximations in the portrayal of 3D objects, posed a secondary modelling challenge. While flat objects can be accurately depicted, curved ones require heightened precision, leading to an increased number of faces and vertices within the mesh. Consequently, this necessity amplifies the demand for computational resources and memory allocation. The significant polygon count in mesh models generated from laser scanning or photogrammetry often results in unwieldy file sizes, surpassing the memory capacity of XR applications. Therefore, optimising the polygon count becomes essential to ensure proper visualisation and efficient model utilisation (Fig. 15). For this reason, the second approach was oriented towards reducing the weight of meshes for the development of 3D models and XR environments avoiding the initial approach oriented to high-re models, ensuring they consist not only of lightweight and intricate meshes but were also capable of being transformed into IVOs with light geometry. Various software tools cater to retopology, such as ZBrush, 3D-Coat, and InstantMeshes, each offering unique features for simplifying the creation of low-resolution models from high-resolution ones. Nevertheless, notable distinctions exist in the approaches and tools used for retopology among software like MC Neel Rhinoceros, Blender, and ZRemesher (Gonizzi et al., 2022; Barsanti & Guidi 2018; Webster 2017). Rhinoceros, primarily focused on NURBS modelling, supports retopology operations on polygonal meshes, albeit with a more manual process compared to Blender.

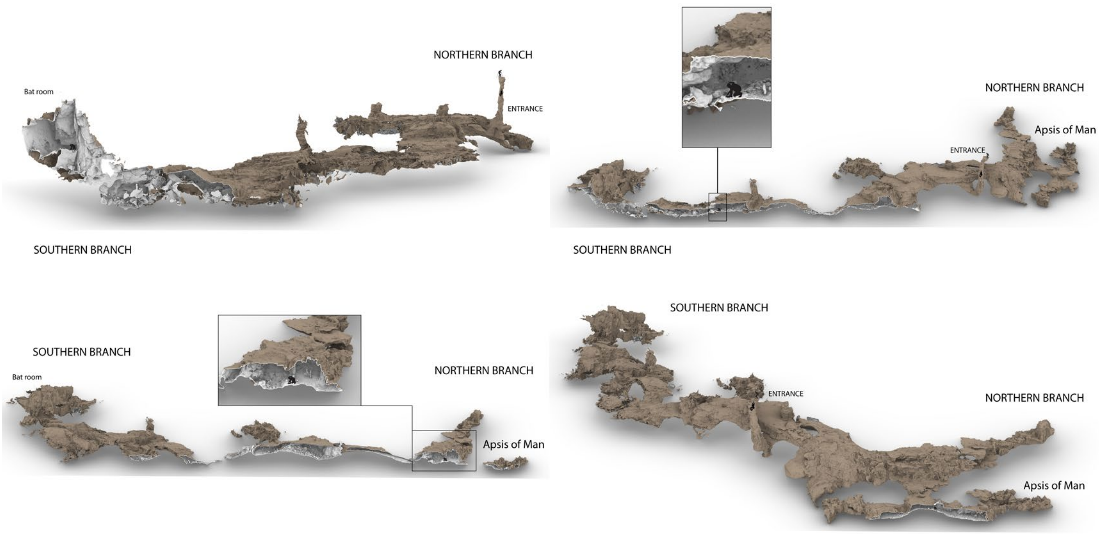

Fig. 16 - The comprehensive NURBS model of Lamlaunga Cave incorporates the identification of both the northern and southern branches, as well as the overlap zone, ensuring accurate georeferencing of digitised data following the second survey campaign in 2023. The NURBS model allows for dimensional control over time. Through segmentation tools, it is possible to extract quantities such as volumes, areas, thicknesses and metric sections according to needs.

In Blender, retopology is seamlessly integrated through tools like the "Remesh" modifier and the "RetopoFlow" addon, facilitating precise creation of new topologies on existing models. The open-source nature of Blender and its vast developer community contribute to continuous improvement and updating of retopology tools, with the "Decimate" modifier serving as a key tool for reducing polygon count while preserving model complexity, thus enhancing virtual environment performance. Blender's specialised retopology tools, including the "Remesh" modifier and the "RetopoFlow" addon, enhanced flexibility and precision in cave modelling endeavours by simplifying the process of establishing new topologies on pre-existing models. Similarly, the inherent flexibility of retopology within ZRemesher enabled the adaptation of the model's topology to align precisely with project requirements, proving invaluable when navigating intricate shapes and details typical of cave environments (Fig. 16). Furthermore, upon the completion of retopology procedures, the model can be seamlessly exported in various formats compatible with diverse software platforms. This interoperability facilitated effortless sharing and collaborative endeavours among peers and researchers, thereby augmenting the overall efficiency of the modelling process. The applied process entailed the integrated utilisation of various listed software, tailored to the specific portion of the cave to be rendered. This approach aimed to employ precise commands corresponding to the unique requirements and shapes to be converted. In this particular endeavor, aimed at encompassing elements previously unaddressed and specifically automating the transformation process to complement the primary interests of digitising both branches of the cave, a third approach was undertaken.

In the realm of reverse engineering software, a multitude of specialised packages exists, offering varying degrees of automation for this process, ranging from moderately priced to exorbitantly expensive. Plug-ins are also available to augment the capabilities of platforms like Rhinoceros,

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though they come at a cost. Efforts were made to utilise reverse engineering software, specifically Geomagic Design X, alongside the mesh-to-NURBS command in MC Neel Rhinoceros, to execute necessary transformations. This involved meticulous examination and rectification of common mesh errors, including auto-intersections, non-manifold topologies, redundant and tangled geometries, and other irregularities. Rectification of such errors was deemed essential, given their potential to undermine subsequent operations, particularly in auto-surfacing aimed at fitting NURBS to the underlying meshes. Consequently, rectifying these discrepancies necessitated an organised sequence of semi-automated procedures. The MeshToNurb command transmuted a faceted mesh structure into a faceted NURBS counterpart, crafting individual NURBS surfaces corresponding to each mesh face and amalgamating them into a polysurface. Notably, quadrilateral mesh elements were converted into 4-sided untrimmed degree 1 NURBS surfaces, with the defining edges of these surfaces mirroring the lines representing the mesh face's boundaries. Mesh triangles were transformed into either trimmed or untrimmed planar NURBS surfaces, contingent upon the TrimTriangularFaces command line option.

Following the preliminary experimental phase, attempts were made to extend this methodology to a larger dataset. However, it became evident that MeshToNurb excelled primarily in converting low-polygon count meshes, predominantly planar, into NURBS surfaces conducive for further manipulation. Consequently, to complement rather than supplant the initial approaches, the software Geomagic Design X was introduced as a third modality, aligning with the exigencies of research investigation. This complex process began by addressing various common mesh errors, such as auto-intersecting, non-manifold, crossing, redundant, tangled, reversed faces, small tunnels, and duplicated vertices. Correcting these errors was crucial to ensure favorable outcomes when applying the auto-surfacing command to fit NURBS onto the designated meshes. Treating these elements involved a meticulous sequence of steps. It started with duplicating the original chunk from Agisoft Metashape and adjusting the bounding box around each element. Detailed depth maps were then generated at the highest resolution possible, serving as foundational data for creating meshes. Once generated, the meshes were exported in .obj format. Upon importing the .obj files into Geomagic Design X, the focus shifted to rectifying topological errors and creating a watertight mesh. NURBS geometries were subsequently fitted automatically onto the meshes, ensuring seamless integration of the desired surfaces. The process concluded with importing the .igs file into Rhinoceros, where meticulous attention was given to prevent any scaling or movement of the single object, thereby preserving the model's integrity.

XR ENVIRONMENTS FOR ACCESSIBLE DISCOVERY OF LAMALUNGA CAVE'S TREASURES

In the realm of virtual heritage, the Scan-to-BIM-to-XR process utilises various applications and file formats to create digital models that enable seamless navigation, control, and sharing. Adopting a holistic approach, which leverages advanced 3D tools while reducing reliance on diverse exchange formats—whether proprietary or open-source—proves promising for representing and disseminating the intrinsic values of cultural heritage. Integrating innovative Application Programming Interfaces (APIs) guides models towards digitally shareable representations like digital twins and web-XR platforms. The pursuit of digital representation and visual communication has intensified, spurred by the necessity to effectively present associated information within semantic models. Initially, efforts concentrated on developing a web-XR platform for the Altamura cave, enhancing visitor experiences through interactive digital representations. This user-centric approach defined the rules and dynamics between users, mobile devices, virtual environments, and their contents.A nuanced grasp of available technologies has been pivotal in enriching visitor experiences, offering varying levels of interaction with each technology. This surge in interactivity empowers virtual visitors to deeply engage with dynamic environments, archival materials, and storytelling, thereby unlocking new avenues for virtual representation. Pioneering technological advancements have fueled an experimental phase in the XR domain, enhancing interaction and accessibility by fostering deeper engagements between models, users, and devices. The research case study focuses on virtual visual storytelling, meticulously tailored to encapsulate historical, cultural, and biological contexts. Content, geometry, and dynamics form the three foundational pillars defining an interactive experience and imbuing it with uniqueness.

Content encompasses objects and associated information within the environment, serving as the cornerstone of the virtual experience, manipulable by users through specific input mechanisms. Geometry within the virtual realm outlines the physical appearance, including the layout, size, and spatial positioning of objects. Dynamics encapsulate the interaction rules governing the contents within the virtual environment, facilitating interactions between objects and users. Well-crafted dynamics aim to render the virtual experience as immersive as possible, empowering users to engage with virtual cultural heritage akin to real-world archaeological and anthropological discoveries. To make the treasures of the Lamalunga cave accessible and user-friendly to a wide audience, including experts and virtual tourists, this study proposes the development of three types of XR environments:

Local VR App - This immersive historical experience is accessible via PCs and VR headsets. It integrates technological advancements with historical narratives, providing users with a deeply immersive journey into the cave's history and significance.

Heritage Metaverse - Aimed at democratising cultural immersion, this web-VR application

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enables access across devices—including VR headsets, tablets, smartphones, and PCs without additional software installations. By leveraging web-based technology, it broadens access to the virtual cave experience, overcoming barriers of accessibility and device compatibility.
XR App with Volumetric Avatar and Interactive Virtual Objects (IVOs) - This initiative aims to create a dynamic virtual metaverse using visual programming languages (VPL). Integrating volumetric avatars and IVOs allows users to engage and explore the cave environment in innovative ways, fostering a deeper connection with the historical site.
The initial step in crafting immersive environments involved importing static models into the chosen development environment, such as Unreal Engine, Twinmotion, or Unity. The choice of XR platform has been influenced by the ability of the former two to collect a large quantity of 3D outputs and synchronise them in real-time with the modelling software used, such as Rhinoceros. In the contemporary landscape of architectural visualisation and immersive design, the seamless integration of 3D models into virtual environments holds paramount importance. Traditionally, the process of importing models from diverse modelling and CAD software into visualisation engines such as Twinmotion and Unreal Engine has been fraught with complexities and inefficiencies. However, with the advent of the Datasmith add-in, a paradigm shift has ensued, empowering designers and developers with unparalleled capabilities to streamline their workflow and enhance productivity. In particular, the vast amount of processed and modelled data has necessitated the definition of a process capable of exponentially reducing the creation of an XR environment in geometric terms. By circumventing the need for intermediary file formats and manual conversion processes, Datasmith expedites the importation process, enabling users to seamlessly transition from their native design environments to the visualisation engine of choice. This streamlined approach not only saves valuable time but also mitigates the risk of data loss or corruption during the importation process, ensuring the preservation of data integrity and fidelity. Figure 17 demonstrates the process of enriching the general cave model with additional content within the modelling software before seamlessly importing it into Twinmotion for scene finalisation. Once synchronised, these models undergo further optimisation processes aimed at enhancing performance without compromising visual fidelity. Optimisation techniques included geometry simplification, texture optimisation, and the creation of proper meshes to manage rendering complexity efficiently.
Moreover, the assignment of appropriate materials and high-resolution textures derived from photogrammetric surveys to static models has proven indispensable in attaining realism and immersion within the environment. Orthophotos and photogrammetry textures offered a meticulous representation of archaeological features, capturing intricate details and surface characteristics with precision. This heightened level of realism amplified the authenticity of digital models, enabling both researchers and the

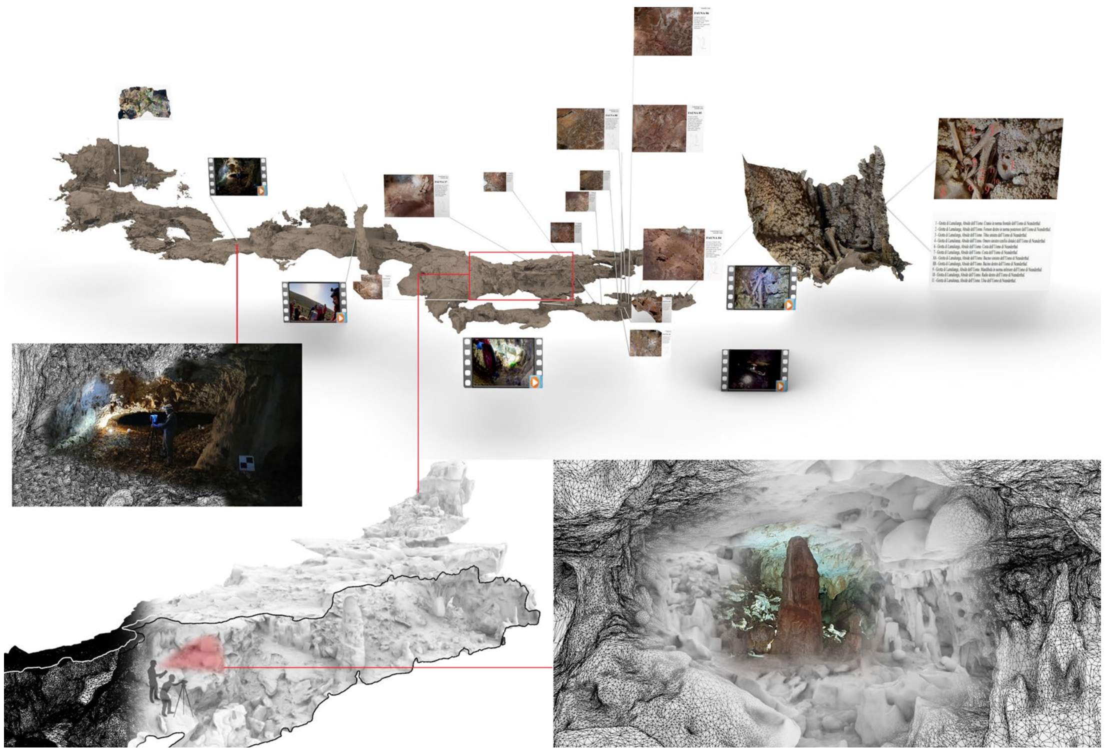

Fig. 17 - The comprehensive NURBS model of the cave integrated multimedia files and highly detailed models of various digitised remains before real-time synchronisation in Twinmotion. Through the application of specific retopology techniques, an elevated level of geometric complexity was achieved, transitioning from mesh models composed of triangular faces (left side of the image) to NURBS models capable of conforming to the required shape (right side of the image).

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final users to engage with the treasure cave in a profoundly immersive manner.
Furthermore, meticulous attention to lighting design plays a pivotal role in crafting atmosphere and depth. The strategic use of dynamic and static lighting sources, complemented by global illumination techniques, contributes significantly to the overall realism of the environment. Particularly, to maximize immersion, light sources were positioned in alignment with the arrangement of the numerous spotlights used to illuminate the cave during two survey phases. Once the general environment was created, the development process focused on increasing levels of interactivity. The immersive environment necessitated dynamic elements to enhance engagement and interaction. Objects within the environment were animated to simulate movement or respond to user input, thereby enhancing immersion. Additionally, the integration of IVOs, such as clickable objects or interactive interfaces, promotes user engagement and facilitates experiential learning.
To achieve a high yet sustainable and comprehensible level of user interactivity and IVOs, Unreal Engine was selected as the development tool to create an XR App with Volumetric Avatar and IVOs.
By utilising specific blueprints, it was possible to integrate visual programming language into a single process, allowing static models to come to life. In particular, the remains of the Neanderthal man and the main digitised fauna were enriched with functions and information aimed at increasing the informational value of the virtual experience.
The interaction between the user and the scene was defined based on a human-centric approach, capable of placing the human being at the centre of interactive experience design, with the ultimate goal of meeting its needs and enhancing its experience.
The utilisation of the first-person template afforded the user a perspective akin to viewing the virtual world through the eyes of the character being portrayed. Such an approach not only heightens immersion but also cultivates a profound sense of presence within the virtual realm, thereby augmenting the user's agency and sense of direct involvement within the environment. Finally, the last step involved performance optimisation and testing the interoperability level of the developed XR environment. Optimising performance has been crucial to ensure the smooth and seamless operation of immersive environments across different platforms and devices.
Techniques such as polygon reduction, texture compression, and efficient resource management were employed to maximize performance without sacrificing quality.The decision to utilise Twinmotion and Unreal Engine proved to be of utmost importance in achieving and developing various XR environments while avoiding the exponential usage of software and development tools.
Recent advancements in Twinmotion have enabled the creation of a Local VR App compatible with desktop devices and VR headsets like the Meta Quest 2, while seamlessly transitioning the same environment to web-VR on mobile devices (Fig. 18). The final packaging and cloud migration tools have significantly reduced computational requirements and export procedures compared to Unreal Engine and Unity. In contrast, Unreal Engine required a deep understanding of computer science principles during XR app packaging. Essential steps included meticulous configuration of project settings for optimal performance, such as screen resolution, graphical settings, access permissions, and other specifics.
After fine-tuning these settings, the project was compiled to generate necessary files, including game code, multimedia assets, and graphical resources. Choosing the target platform (e.g., Windows, macOS, Android, iOS) and customising packaging settings were critical decisions to ensure performance and meet project requirements. Unreal Engine executed the packaging process, compiling the project and creating the application package based on the third-person template (Fig.19)

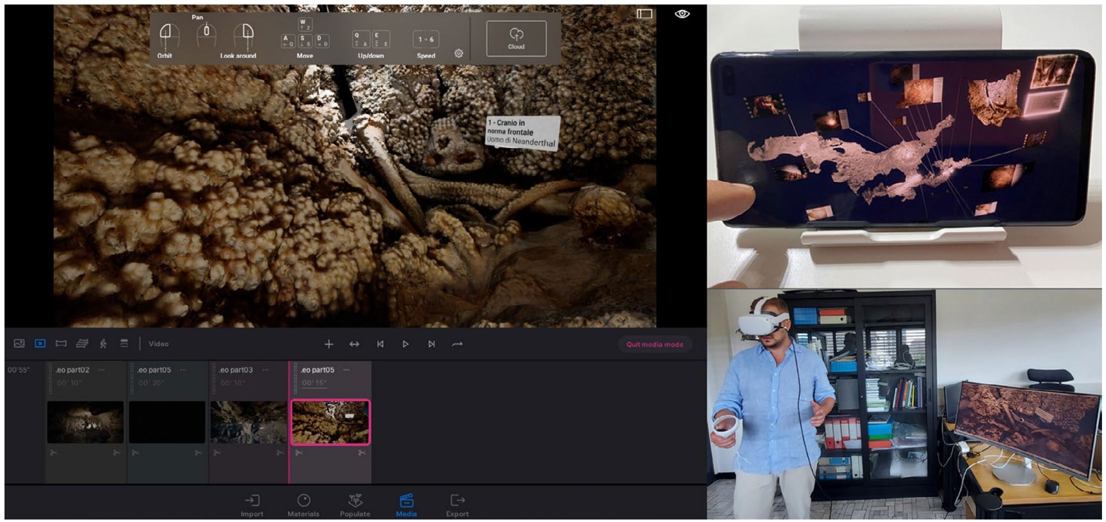

Fig. 18 - The digital models were seamlessly integrated into Twinmotion, enabling simultaneous creation of 3D animations, views, panoramas, cloud-based XR project conversion, and a dedicated VR gaming app, all within a unified environment, ensuring remote access.

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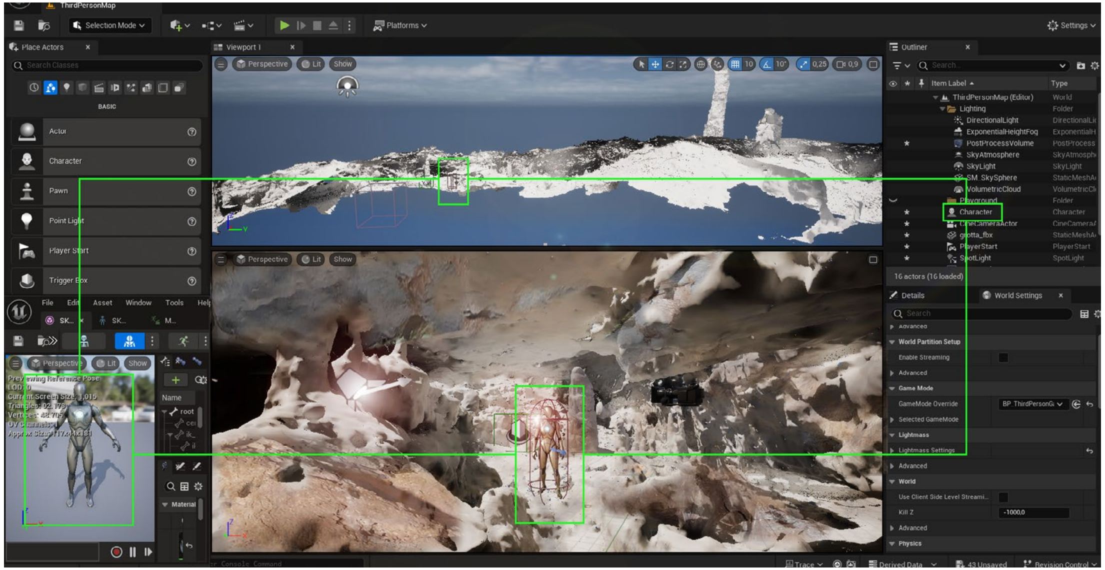

Fig. 19 - The cave model imported into Unreal Engine, along with specific blueprints for third-person navigation, aimed to increase immersion and interaction with IVOs. It conveyed human scale within spaces and enabled direct interaction with faunal and Neanderthal man remains

INTEGRATED METHODOLOGIES: A TRANSDISCIPLINARY RECONSTRUCTION OF THE CONTEXT IN A CONSERVATIVE KEY

The Lamalunga Cave represents an exceptional field of investigation, both for the almost intact karst context, for the presence of the most archaic and complete Neanderthal known in the world, today immersed in an environment and a microclimate almost constantly stable or with slight variations.These elements make the Altamura Man of extreme relevance to understanding the evolutionary history of the Neanderthal species, but not only. His study could open new horizons of knowledge of our evolutionary history of Sapiens as our species interacted and joined the Neanderthal, many of us retain in their DNA traces of this union. To investigate these aspects it is necessary to extend the gaze from Man to the surface of the cave, to its geological and sedimentological formation, as well as to the traces of material culture and anthropic attendance that may have affected the cave in many ancient periods.Even after 30 years of discovery, thanks to the continuous evolution of science and technology, the cave and the Neaderthal man constitute a field of research in which to implement complex works, innovative, multidisciplinary, and synergistic between professionals and bodies from different sectors, from those aimed at the protection and conservation of the artifact, to the cognitive and research sector, all in a transversal vision that allows the various actors to dialogue on common questions, each with its methods. Global Archaeology for the first time is applied to the context of Lamalunga - that is, an implementation of all the disciplines useful for a diachronic understanding of natural, archaeological, and historical events that affected the territorial compartment of the cave - allows authors to connect the underground world with the outside. Different and impenetrable worlds today that surely in ancient had to generate varied perceptions in the inhabitants of the territory, and only thanks to the application of new methodologies of interrogatable and interoperable documentation are we now able to reconstruct in a hypothetical key.

The three-dimensional documentation is being accompanied for the first time by systematic archaeological surveys in the cave, as well as surface surveys of the karst extrados, to verify the presence of stratigraphies and deposits of archaeological interest, defining where possible chronologies and phases of attendance. The primary objective is to explore the context with a conservative approach, investigating the Neanderthal karst environment; given the recent scientific acquisitions about the co-evolution of rocks and microbial communities has carried out monitoring of microorganisms inside the cave with an innovative and experimental scientific approach to classical microbiological, electron microscopy, metagenomic and metabolomic character. Specifically, the activities were aimed at defining the microbial community in the surrounding environment, verifying possible forms of biodegradation attributable to various types of environmental changes, in fact evaluating the biodiversity and microbial metabolism inside the Lamalunga Cave about the geological substrate, all through a necessary comparison with similar karst environments.

The cave is also investigated to verify its stages of anthropisation not only in the Neanderthal period but also in any more ancient or more recent chronological phases, at the same time identify the ancient accesses through the most modern technologies in which to correlate high-resolution survey of the intrados and the extrados of the cave with 3D geognostic investigations that will show us cracks and obliterated accesses. All in a perspective of a multidisciplinary and evolutionary understanding of the karst context to be correlated with the Neanderthal presence and with the most recent fauna.

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Before the advent of laser-based 3D modelling, documenting the Altamura Cave and its artefacts required a laborious manual process involving traditional measurements and photographic surveys. This approach was often lengthy and exhausting, and the collected information could be limited or imprecise. However, with the introduction of laser scanning technology, archaeologists gained the ability to acquire high-resolution data quickly and accurately, enabling them to create extremely detailed digital models of the cave and its contents. The revolution in our understanding of the Altamura Cave and the Neanderthal remains found therein was triggered by accurate 3D modelling derived from laser data. This sophisticated method of data acquisition has opened up new horizons for professionals involved in the preservation process, allowing for the creation and management of detailed 2D/3D/XR digital representations of the cave and its contents, offering an unprecedented view of its morphology and the arrangement of artefacts within. The use of these 3D models has opened up new avenues for research and analysis. Archaeologists can now examine the smallest details of the cave and its artefacts, studying the spatial arrangement of objects and identifying possible patterns or significant correlations. 3D modelling has also allowed experts to view the cave from various perspectives and angles, providing a more comprehensive understanding of its overall structure and morphology
In particular, thanks to the analysis and interpretation of models correlated with external data, critical points have been identified, such as tunnels that almost resurface near paths and fields destined for agriculture. To ensure broad accessibility, initiatives have been undertaken to engage both professionals and virtual as well as physical tourists. At the archaeological site entrance, a dedicated tourist information panel has been installed. This panel provides detailed descriptions of the site and ongoing research. Additionally, it includes a QR code that directs visitors to a 3D animation showcasing the findings discussed in this study (Fig. 20).

Regarding the Neanderthal remains found in the Altamura Cave, 3D modelling has also allowed for an unprecedented level of detail in examining the artefacts context from an archaeological, anthropological and conservative point of view. This approach has led to discoveries and interpretations about the life and habits of Neanderthals, significantly enriching our knowledge of this prehistoric species.
There are many questions still open and related to the way he entered the cave and arrived in the apse, if voluntarily or forced for example, what were the possible accesses and when they occluded, as well as what were the phases of frequenting the environment even in recent times. To investigate these aspects, we must extend our gaze from Man to the cave's surface, to its geological and sedimentological formation, as well as to the traces of material culture and anthropic attendance that may have affected the cave in many ancient periods; the virtual and metrically correct reconstruction of the context allows authors to remotely investigate every aspect ensuring the preservation of the site (National Geographic Italia, 2024).

Fig. 20 - The cave entrance now features a tourist information panel with details about the archaeological site and ongoing research. A QR code on the panel links to a 3D animation that illustrates the findings and immerses visitors into the heart of the cave.

CONCLUSION

This study underscores the pivotal role of Science of Representation in the documentation of archaeological sites, significantly contributing to the conservation, research, education, and enrichment of global cultural heritage through the innovative application of advanced digital technologies. Specifically, the research highlights the transformative impact of reality-based 3D models in preserving the archaeology of Lamalunga cave and its priceless Neanderthal artifacts. The integration of digital models and 3D survey data has not only revolutionised access to previously inaccessible archaeological sites but has also introduced novel concepts like virtual heritage and extended reality.
For the first time in the site's history, 28 faunal remains, Neanderthal artifacts, and the southern branch have been meticulously documented, geared towards a digitisation process benefiting professionals engaged in cave preservation and virtual tourists alike. Leveraging advanced 3D modeling techniques such as NURBS algorithms and mesh retopology, highly detailed and precise digital replicas, alongside XR experiences of the cave and its contents, were developed. These models not only faithfully preserve the intricate physical characteristics of the cave but also uphold the contextual integrity crucial for in-depth analysis and interpretation of archaeological discoveries.
The scrutiny of the proposed apporach has illuminated both the capabilities and constraints of digital models for XR applications. While enhancing preservation, accessibility, and inclusivity, these technologies present challenges such as the demand for specialised expertise and the complexity of maintaining historical accuracy in models. Looking ahead, continual advancements in digital technology and interdisciplinary collaboration will be pivotal in surmounting these challenges and harnessing the full potential of innovative methodologies in archaeological research and cultural heritage preservation.

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[1] This research is the result of a collaborative and meticulously coordinated effort among the authors. F.B. led the writing and composition of all paragraphs, ensuring cohesion across sections, particularly in defining the proposed approach.
F.B. and F.R. jointly handled the paragraph "Research Progress: The Second 3D Survey Campaign (2023) of the Southern Branch of the Cave."
E.D. and G.C. managed the paragraph "Integrated Methodologies: A Transdisciplinary Reconstruction of the Context in a Conservative Key" and worked closely with F.B. to oversee the entire content.

REFERENCES

Agostini, S. (2010). Lineamenti geomorfologici della Grotta di Lamalunga. In Dire in Puglia - Ministero per i Beni e le Attività Culturali - Direzione Regionale per i Beni Culturali e Paesaggistici della Puglia, Città di Castello (PG) (pp. 17- 21).

Bahirat, K., Lai, C., Mcmahan, R. P., & Prabhakaran, B. (2018). Designing and evaluating a mesh simplification algorithm for virtual reality. ACM transactions on multimedia computing, communications, and applications (TOMM), 14(3s), 1-26.

Banfi, F. (2023). Virtual Heritage | from 3D modelling to HBIM and extended reality. Maggioli Editore. ISBN: 9788891661937

Banfi, F., Dellù, E., Stanga, C., Mandelli, A., Roncoroni, F., Sivilli, S., Pepe, G., and Cacudi, G. (2023). Representing intangible cultural heritage of humanity: from the deep abyss of the past to digital twin and XR of the neanderthal man and lamalunga cave (altamura, apulia), Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLVIII-M-2-2023, 171–181.

Barsanti, S. G., & Guidi, G. (2018, June). A New Methodology for the Structural Analysis of 3D Digitized Cultural Heritage through FEA. In IOP Conference Series: Materials Science and Engineering (Vol. 364, No. 1, p. 012005). IOP Publishing.

Bayarri, V., Prada, A., García, F., Díaz-González, L. M., De Las Heras, C., Castillo, E., & Fatás, P. (2023). Integration of remote-sensing techniques for the preventive conservation of Paleolithic cave art in the karst of the Altamira cave. Remote Sensing, 15(4), 1087.

Branca, M., & Voltaggio, M. (2010). Studi cronologici eseguiti sulle concrezioni carbonatiche della Grotta di Lamalunga. In Dire in Puglia - Ministero per i Beni e le Attività Culturali - Direzione Regionale per i Beni Culturali e Paesaggistici della Puglia, Città di Castello (PG) (pp. 55-60).

Caramelli, D. et al. (2010). The Analisi Paleogenetica del Neanderthal di Altamura. In Dire in Puglia - Ministero per i Beni e le Attività Culturali - Direzione Regionale per i Beni Culturali e Paesaggistici della Puglia, Città di Castello (PG) (pp. 45-54).

Cardia, S., Langella, F., Pagano, M., Palma, B., Sabato, L., Tropeano, M., & Parise, M. (2024). 3D digital analysis for geo-structural monitoring and virtual documentation of the saint Michael cave in Minervino Murge, Bari (Italy). Digital Applications in Archaeology and Cultural Heritage, 32, e00308.

Champion, E. (2021). Virtual heritage: a guide (p. 153). Ubiquity Press.

Cignoni, P., Montani, C., & Scopigno, R. (1998). A comparison of mesh simplification algorithms. Computers & Graphics, 22(1), 37-54.

De Waele, J., Fabbri, S., Santagata, T., Chiarini, V., Columbu, A., & Pisani, L. (2018). Geomorphological and speleogenetical observations using terrestrial laser scanning and 3D photogrammetry in a gypsum cave (Emilia Romagna, N. Italy). Geomorphology, 319, 47-61.

Di Vincenzo, F. et al. (2019). Distinct among Neanderthals: the scapula of the skeleton from Altamura, Italy. Quat. Sci. Rev., 217, 76-88.

Elagiry, M., Charbel, N., Bourreau, P., Di Angelis, E., & Costa, A. (2020). IFC to building energy performance simulation: a systematic review of the main adopted tools and approaches. Proceedings of the BauSIM.

European Commission (2021a). Digital Europe Programme.

European Commission (2021b). Digital Europe Programme.

Fiore, I., Cerilli, E., & Tagliacozzo, A. (2018). GIS e analisi spaziale intra-sito: i resti ossei faunistici della Grotta di Lamalunga (Altamura, BA), in Applicazioni tecnologiche allo studio di contesti paleolitici e mesolitici italiani. Incontri Annuali di Preistoria e Protostoria, 4, 94-97.

Franc, M. (2002). Methods for polygonal mesh simplification: technical report no. DCSE/TR-2002-01.

García-Bustos, M., Rivero, O., Bustos, P. G., & Mateo-Pellitero, A. M. (2023). From the cave to the virtual museum: accessibility and democratisation of Franco-Cantabrian Palaeolithic art. Virtual Archaeology Review, 14(28), 54-64.
Giacobini, G., Tagliacozzo, A., & Manzi, G. (2010). Lo scheletro umano e i reperti faunistici della Grotta di Lamalunga: considerazioni tafonomiche. In Dire in Puglia - Ministero per i Beni e le Attività Culturali - Direzione Regionale per i Beni Culturali e Paesaggistici della Puglia, Città di Castello (PG) (pp. 27-32).

Gonizzi Barsanti, S., Guagliano, M., & Rossi, A. (2022). 3D Reality-Based Survey and Retopology for Structural Analysis of Cultural Heritage. Sensors, 22(24), 9593.

Guidi, G., & Angheleddu, D. (2016). Displacement mapping as a metric tool for optimizing mesh models originated by 3D digitization. Journal on Computing and Cultural Heritage (JOCCH), 9(2), 1-23.

Huggett, J. (2020). Virtually real or really virtual: Towards a heritage metaverse. Studies in digital heritage, 4(1), 1-15.

Kaňuk, J., Šupinský, J., Meneely, J., Hochmuth, Z., Šašak, J., Gallay, M., & Callieri, M. (2024). Laser Scanning of a Complex Cave System during Multiple Campaigns: A Case Study of the Domica Cave, Slovakia. In 3D Imaging of the Environment (pp. 56-81). CRC Press.

Kartini, G. A., Gumilar, I., Abidin, H. Z., Yondri, L., Bramanto, B., & Dwisatria, M. I. (2024). 3D model of Pawon Cave: The first prehistoric dwelling discovery in West Java, Indonesia. Digital Applications in Archaeology and Cultural Heritage, 32, e00311.

Lari, M. et al. (2015). The Neanderthal in the karst: first dating, morphometric, and paleogenetic data on the fossil skeleton from Altamura (Italy). J. Hum. Evol., 82, 88-94.

Manzi, G. et al. (2010). La porzione di scapola dell'uomo di Altamura: estrazione, documentazione e analisi morfologica. In Dire in Puglia - Ministero per i Beni e le Attività Culturali - Direzione Regionale per i Beni Culturali e Paesaggistici della Puglia (pp. 39-44).

Micheli, M., Piperno, M., & Vacca, E. (eds.). L'Uomo di Altamura e la Grotta di Lamalunga. ABACO, Forlì (1996).

Ministero della Cultura – PNRR Cultura (2022). Piano Nazionale di Digitalizzazione del Patrimonio Culturale (PND).

DOI: https://doi.org/ 10.20365/disegnarecon.32.2024.6

ISSN 1828-5961

National Geographic Italia, 2023). Viaggio nella Grotta di Lamalunga: alla scoperta dell'Uomo di Neanderthal. Retrieved Sempember 29, 2023, from https://www.nationalgeographic.it/viaggio-nella-grotta-di-lamalunga-alla-scoperta-dell-uomo-di-neanderthal

Oliinyk, M., Bubniak, I., Bubniak, A., Shylo, Y., Vivat, A., Mandzuk, V., & Marko, T. (2024). Exploring the Depths: 3D Modeling of Ukraine's Caves through Terrestrial Laser Scanning and Digital Photogrammetry (No. EGU24-337). Copernicus Meetings.

Pan, Y., Xia, Y., Li, Y., Yang, M., & Zhu, Q. (2023). Research on stability analysis of large karst cave structure based on multi-source point clouds modeling. Earth Science Informatics, 16(2), 1637-1656.

Pedeferri, J., (2024). L'uomo di Neanderthal digitale, dalla storia al futuro. Sky TG24. Retrieved January 24, 2024, from https://tg24.sky.it/tecnologia/now/2024/01/24/uomo-neanderthal-digitale-altamura-archeologia-virtuale

Pereira, J. V. F., Medeiros, W. E., Dantas, R. R., Bezerra, F. H., La Bruna, V., Xavier Jr, M. M., ... & Maciel, I. B. (2024). An integrated 3D digital model of stratigraphy, petrophysics and karstified fracture network for the Cristal Cave, NE-Brazil. Journal of Structural Geology, 178, 105013.

Pesce Delfino V., Vacca E., (1993b). Discovery of an archaic human skeleton in Altamura (Bari-Italy), Anthropologie (Brno), 31, 157-158

Pesce Delfino, V. (1995). Prime considerazioni sul ritrovamento di Altamura: aspetti antropologici e aspetti istituzionali. In Venturo D. (ed.), La Grotta di Lamalunga, Atti Conferenza cittadina 1993, Altamura (pp. 89-97).

Pesce Delfino, V. Vacca, E. Three-dimensional topographic survey of the human remains in Lamalunga Cave (Altamura, Bari, Southern Italy). Coll. Antropol. 28, 113–119 (2004).

Pesce Delfino, V., & Vacca, E. (1993a). An Archaic human skeleton discovered at Altamura (Bari, Italy). Riv Antropol, 71, 249-257.

Pesce Delfino, V., & Vacca, E. (1994). Report of an archaic human skeleton discovered at Altamura (Bari), in the "Lamalunga" district. Human Evolution, 9, 1-9.

Pfeiffer, J., Rutzinger, M., & Spötl, C. (2023). Terrestrial laser scanning for 3D mapping of an alpine ice cave. The Photogrammetric Record, 38(181), 6-21.

Riga, A. et al. (2020). In situ observations on the dentition and the oral cavity of the Neanderthal skeleton from Altamura (Italy). PLoS ONE 15, e0241713.

Rodriguez-Garcia, B., Guillen-Sanz, H., Checa, D., & Bustillo, A. (2024). A systematic review of virtual 3D reconstructions of Cultural Heritage in immersive Virtual Reality. Multimedia Tools and Applications, 1-51.

Signorile, L. (2023). Abissi del Tempo: la mostra che celebra i 30 anni della scoperta dell'Uomo di Altamura National Geographic Italia. Retrieved July 10, 2024, from https://www.nationalgeographic.it/abissi-del-tempo-la-mostra-che-celebra-i-30-anni-della-scoperta-dell-uomo-di-altamura

Vanghi, V., Frisia, S., & Borsato, A. (2017) Genesis and microstratigraphy of calcite coralloids analysed by high resolution imaging and petrography. Sedimentary Geology, 359, 16-28.

Webster, N. L. (2017). High poly to low poly workflows for real-time rendering. Journal of visual communication in medicine, 40(1), 40-47.

Wisher, I., Pettitt, P., & Kentridge, R. (2023). The deep past in the virtual present: developing an interdisciplinary approach towards understanding the psychological foundations of palaeolithic cave art. Scientific Reports, 13(1), 19009.

DOI: https://doi.org/ 10.20365/disegnarecon.32.2024.6